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MODELING AND PERFORMANCE ENHANCEMENTS OF A GAS TURBINE COMBINED CYCLE POWER PLANT

THAMIR KHALIL IBRAHIM

Thesis submitted in fulfilment of the requirements
for the award of the degree of
Doctor of Philosophy in Mechanical Engineering

FACULTY OF MECHANICAL ENGINEERING
UNIVERSITI MALAYSIA PAHANG

SEPTEMBER 2012

SUPERVISOR'S DECLARATION

I hereby declare that I have checked this thesis and in my opinion, this thesis is adequate in terms of scopes and quality for the award of the degree of Doctor of Philosophy in Mechanical Engineering.

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NOMENCLATURES

List of Symbols

Symbol	Meaning and units
A_i	The linguistic label from the fuzzy set
AFR	Air-fuel ratio
C_{pa}	The specific heat of the air (kJ/kg.K)
C_{pf}	The specific heat of the fuel (kJ/kg.K)
C_{pg}	The specific heat of flue gas (kJ/kg.K)
f	The fuel-air ratio
h	Enthalpy (kJ/kg)
h_{1f}	The heat loss factor in the heat recovery steam generator
LHV	The lower heating value (kJ/kg)
$\dot{m}_a$	The air mass flow rate (kg/s)
$\dot{m}_f$	The fuel mass flow rate (kg/s)
$\dot{m}_g$	The mass flow rate of the exhaust gases through the gas turbine (kg/s)
$\dot{m}_{fad}$	The additional fuel burning the second combustion chamber
$O_{1,i}$	the output of the i^{th} node in the first-layer
P	The net power output of the turbine (MW)
p	Pressure (bar)
p_1	Compressor inlet pressure (bar)
p_2	Compressor outlet air pressure (bar)
Q_{add}	The heat supplied (kJ/kg)
Q_{av}	The heat available with exhaust gases from gas turbine cycle (kJ/kg)
Q_{sh}	The superheater duty (kJ/kg)
r_p	Pressure ratio
S	Entropy (kJ/K)
SFC	The specific fuel consumption (kg/kW.h)
T	Temperature (K)
T_1	Compressor inlet air temperature (K)

T_2	Compressor outlet air temperature (K)
T_{2s}	The isentropic temperature of outlet compressor (K).
T_a	The average temperature $(T_2+T_1)/2$ (K)
T_{ap}	The approach points (K)
T_f	The temperature of fuel (K)
T_{pp}	The pinch point (K)
T_s	The saturation steam temperature (K)
T_{w1}	The temperature of water entering the economizer (K)
T_{w2}	The temperature of water entering the evaporator (K)
v_f	Specific volume of the water (m^3/kg)
W_c	The work of the compressor (kJ/kg)
W_{Gnet}	The net work of the gas turbine (kJ/kg)
$\overline{W_i}$	The normalized firing strength from layer 3
W_p	The work of the pump (kJ/kg)
W_{snet}	The work net of the steam turbine cycle (kJ/kg)
W_{st}	The work of the steam turbine (kJ/kg)
W_t	The shaft work of the turbine (kJ/kg)
x	The input to node *I*
x	The effectiveness of intercooler (heat exchanger)

Greek Symbols

Symbol	**Meaning**
ε	Effectiveness of the regenerative heat exchanger
ρ	Density (kg/m^3)
γ	Specific heat ratio
γ_a	Specific heat ratio of air
γ_g	Specific heat ratio of gases
η	Efficiency
η_C	Isentropic compressor efficiency
η_{chp}	The high-pressure compressor efficiency

η_{clp}	The low-pressure compressor efficiency
η_{db}	The supplementary firing efficiency
η_{HPT}	The high-pressure turbine efficiency
η_{LPT}	The low-pressure turbine efficiency
η_{m}	The mechanical efficiency of the compressor and turbine
η_{p}	The water pump efficiency
η_{st}	The steam turbine efficiency
η_{stc}	The steam turbine cycle thermal efficiency
η_{t}	Isentropic turbine efficiency
η_{th}	The thermal efficiency of the gas turbine

Subscripts

Symbol	**Meaning**
1,2…etc	State number
a	Air
add	Added
all	Overall
ap	Approach point
av	Average
c	Compressor
cond	Condenser
f	Fuel
fdb	Fuel burning in the supplementary firing
g	Gases
Gnet	Gas turbine net work
HP	High pressure
IP	Intermediate pressure
LP	Low pressure
p	pump
pp	Pinch point

RH	Reheated pressure
S	Isentropic
s	Saturated steam
snet	Steam turbine work net
ss	Superheated steam
st	Steam turbine
stc	steam turbine cycle
w	Water
w1	Inlet water to economizer
w2	Inlet water to evaporator

LIST OF ABBREVIATIONS

ANFIS	Adaptive neuro-fuzzy inference system
AFR	Air fuel ratio
ANN	Artificial neural network
C	Compressor
C.C	Combustion chamber
CCGT	Combined cycle gas turbine power plant
CCI	First combustion chamber
CCII	Second combustion chamber
D	Drum
DPCC	Dual pressure combined cycle power plant
DSH	The degree of superheat
FAR	Fuel air ratio
GT	Gas turbine
HE	Heat exchanger
HGT	Reheated gas turbine
HP	High pressure
HPC	High pressure compressor
HPT	High pressure turbine
HRSG	Heat recovery steam generator
IEA	International Energy Agency
IGT	Intercooler gas turbine
IGTCC	Intercooler gas turbine combined cycle
IHGT	Intercooler-Reheat Gas Turbine
IHGTCC	Intercooler reheats gas turbine combined cycle
IP	Intermediate pressure
IPT	Intermediate pressure turbine
IRGT	Intercooler-Regenerative Gas Turbine
IRHGT	Intercooler-Regenerative-Reheat Gas Turbine

IRHGTCC	Intercooler regenerative reheats gas turbine combined cycle
IRTGT	Intercooler-Regenerative-Two-Shaft Gas Turbine
IRTGTCC	Intercooler regenerative two-shaft gas turbine combined cycle
ISO	International standards organization
ITGT	Intercooler-Two Shaft Gas Turbine
ITGTCC	Intercooler two-shaft gas turbine combined cycle
LHV	Lower Heating Value
LP	low pressure
LPC	Low pressure compressor
LPT	Low pressure turbine
PES	Performance enhancing strategies
RGT	Regenerative gas turbine
RGTCC	Regenerative gas turbine combined cycle
RH	Relative humidity
RHGT	Regenerative-Reheat Gas Turbine
RHGTCC	Regenerative reheats gas turbine combined cycle
RTGT	Regenerative-Two Shafts Gas Turbine
RTGTCC	Regenerative two-shaft gas turbine combined cycle
SFC	Specific fuel consumption
SGT	Simple gas turbine
SGTCC	Simple gas turbine combined cycle
SPCC	Single pressure combined cycle power plant
ST	Steam turbine
TGT	Two-shaft gas turbine
TIT	Turbine inlet temperature
TPCC	Triple-pressure combined cycle power plant
TPRCC	Triple-pressure steam-reheat combined cycle power plant
TPRHCC	Supplementary firing triple-pressure steam-reheat combined cycle
TTD	The terminal temperature difference

ABSTRACT

This thesis deals with modelling and performance enhancements of a gas-turbine combined cycle power plant. A clean and safe energy is the greatest challenges to meet the requirements of green environment. These requirements given way the long time governing authority of steam turbine (ST) in the world power generation, and gas turbine (GT) and its combined cycle (CCGT) will replace it. Therefore, it is necessary to predict the characteristics of the CCGT system and optimize its operating strategy by developing a simulation system. Several configurations of the GT and CCGT plants systems are proposed by thermal analysis. The integrated model and simulation code for exploiting the performance of gas turbine and CCGT power plant are developed utilizing MATLAB code. New strategies for GT and CCGT power plant's operational modelling and optimizations are suggested for power plant operation, to improve overall performance. The effect of various enhancing strategies on the performance of the CCGT power plant (two-shaft, intercooler, regenerative, reheat, and multi-pressure heat recovery steam generator (HRSG)) based on the real GT and CCGT power plants. An extensive thermodynamic analysis of the modifications of the most common configuration's enhancements has been carried out. The performance code for heavy-duty GT and CCGT power plants are validated with the real power plant of Baiji GT and MARAFIQ CCGT plants the results have been satisfactory. The simulating results show that the reheated GT has a higher power (388MW) while the higher thermal efficiency occurs in the regenerative GT (52%) with optimal pressure ratio and turbine inlet temperature. The performance enhancing strategies results show that the higher power output occurs in the intercooler-reheat GT strategy (404MW). Furthermore, the higher thermal efficiency (56.9%) and lower fuel consumption (0.13kg/kWh) occur in the intercooler-regenerative-reheat GT strategy. The analyses of the HRSG configurations show that the maximum power output (1238MW) occurred in the supplementary triple pressure with reheat CCGT while the overall efficiency was about 56.6%. The intercooler-reheat CCGT strategy has higher power output (1637MW) and the higher overall thermal efficiency (59.4%) and lower fuel consumption (0.047kg/kWh) occur with the regenerative-reheat CCGT strategy. The simulation result shows that the proposed GT system improved 19% of thermal efficiency and 22% of power output. In addition, the proposed CCGT system improved 4.6% of thermal efficiency for and 22.5% of power output. The optimization result shows that the optimum power (1280MW) and the overall thermal efficiency (65%) of the supplementary triple pressure with reheat CCGT. Therefore, the optimization procedure is reasonably accurate and efficient. Thus, the operation conditions and ambient temperature are strongly influenced on the overall performance of the GT and CCGT. The optimum efficiency and power are found at higher turbine inlet temperatures. It can be comprehended that the developed models are powerful tools for estimating the overall performance of the CCGT plants. The energy and exergy analysis models for the GT and CCGT plants are highly recommended for predicting them performance based on inlet air cooling system.

ABSTRAK

Thesis ini menerangkan penambahbaikkan prestasi dan model gas turbin dengan kitaran loji janakuasa. Masalah utama adalah untuk mematuhi piawaian kebersihan dan penjimatan tenaga dalam persekitaran hijau. Piawaian ini menggantikan undang lama turbin gas (ST) dalam penghasilan kuasa dunia gas turbin dan kitaran CCGT. Oleh itu, amat penting untuk memahami ciri system CCGT dan memikirkan strategi optimum operasi melalui system simulasi. Analisa therma mencadangkan pelbagai tatarajah GT dan sistem CCGT seperti kod MATLAB, pembangunan kod simulasi dan model integrasi untuk mengeksploitasi loji janakuasa dan prestasi turbin gas. Strategi baru direka untuk operasi loji janakuasa untuk meningkatkan prestasi keseluruhan berdasarkan model operasi dan pengoptimunan GT dan loji janakuasa CCGT. Strategi-strategi memberi kesan kepada prestasi CCGT (bersama penyejukdalaman,dua-batang,pemanasan semula, penghasilan semula dan HRSG) berdasarkan loji janakuasa sebenar GT dan CCGT.Analisa berdasarkan thermadinamik telah dilakukan pada modifikasi kitaran penambahbaikkan umum. Pengesahan tugasan berat prestasi kod GT dan loji janakuasa dilakukan melalui kuasa sebenar loji janakuasa GT dan MARAFIQ CCGT dengan keputusan yang baik. Keputusan dari simulasi menyatakan pemanasan semula GT mempunyai kuasa yang tinggi sebanyak 388 MW dimana kecekapan tertinggi therma ialah 52 % berlaku pada penghasilan semula GT yang mempunyai suhu dalam tangki dan nisbah mampatan yang optimal. Strategi untuk prestasi penambaikkan menunjukkan kuasa tertinggi penghasilan berlaku pada 404 MW dalam penyejuk-pemanasan semula strategi GT. Tambahan, kurang penggunaan bahan bakar 0.13kg/kWh dan kecekapan therma 56.9% dilihat dalam strategi penyejukkan-generasi semula-pemanasan semula GT. Konfigurasi analisa GT menunjukkan pada tekanan tamabahan tiga bersama pemanasan CCGT, perolehan kuasa maksima adalah 59.4% dan pengurangan penggunaan bahan bakar sebanyak 0.047 kg/kWh berlaku ketika menggunakan strategi generasi semula-pemanasan semula CCGT. Keputusan simulasi menunjukkan system GT yang di usulkan meningkatkan kecekapan therma sebanyak 19% dengan perolehan kuasa sebanyak 22%. Tambahan, system CCGT yang dicadang dalam kajian ini meningkatkan kecekapan therma 4.6% and perolehan kuasa 22.5%. Keputusan penambahbaikan menunjukkan tekanan tambahan tiga bersama pemanasan CCGT mempunyai kuasa optimum sebanyak 1280 MW dan kecekapan therma 65%. Oleh itu, suhu persekitaran dan syarat operasi GT dan CCGT kuat mempengaruhi prestasi. Level optimum kuasa dan kecekapan dapat dilihat berlaku pada suhu turbin gas tertinggi. Jadi, dapat difahami bahawa model yang dibangunkan dalam kajian ini sangat berguna untuk meramal prestasi CCGT loji janakuasa. Penggunaan model analisa ini amtalah dicadangkan untuk GT dan CCGT dalam meramal prestasi berdasarkan penyejukkan system dalaman.

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